RISK MANAGEMENT FOR THE IMPACTS OF CORONAL MASS EJECTIONS, ELECTROMAGNETIC PULSE THREATS AND CLIMATE-RELATED WEATHER EVENTS ON POWER CABLES SUPPORTING THE POTENTIAL OF OFFSHORE WIND ENERGY OFF OF THE NORTHERN EAST COAST OF THE UNITED STATES

by
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Abstract.

The offshore wind industry is in the midst of its technology breakthrough phase, as humankind has experienced recently in other technology breakthroughs such as the internet and the smart phone. Wind turbine capability is growing considerably every few years, and infrastructure is in rapid advancement in hopes to barely keep up. As the offshore wind industry has announced the technology of a 15 MW turbine, a 525 KV HVDC subsea transmission cable has also made its debut, reflecting a capability to support 2 GW, more than 130 of these new turbines.

Offshore Wind power has very positive risk benefits. It has been in a steady decline in price possibly supporting economic feasibility, while also growing in potential for abundance, where it could provide as a solid improvement in CO2 emissions from our power grid. However, there are negative risks that the supportive infrastructure will face. The coastal areas are more susceptible to Earth's weather disasters, mainly hurricanes and tropical storms, and findings also suggest a higher susceptibility to solar weather caused by our sun.

When it comes to addressing these risks and assuring a reliable, resilient power source to the public, there are politics involved. Offshore Wind Energy is new to the energy mix of the United States. As a result, it may face challenges if policy does not maintain an accurate evaluation of these risks into policy.

This study investigates how Offshore Wind Energy in the North Atlantic offshore region of the United States will be affected by recent policy mitigating geomagnetic storm impacts, by analyzing its resiliency to the risk within thresholds presented to and enacted by congress. Findings suggest that future Offshore Wind Energy farms and grid resiliency efforts will benefit from early planning and collaboration efforts, especially in the use of larger cable sizes and HVDC power infrastructure. Conclusive results also suggest key future partnering opportunities in policy to address risks from solar weather events and climate-related events.

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The mentoring support and expertise given by Joseph provided me extraordinary knowledge in the complex science of solar weather and geomagnetic disturbances. His aptitude and dedication of time allowed me to tackle the difficult task of discovering the overlap of two different areas of vast science for the purposes of this thesis.

Also, a special thanks to Daniel Zachary for the guidance, positive energy, and support. Lastly, my dedicated family members; my wife and daughter Josie, who provided me the time and unconditional support through my studies and research, and my brother Bryan, who dedicated hours discussing electrical engineering principles and policy with me.

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Introduction.

The power grid structure of the United States is very complex, because of dynamic challenges, as well as high standards for electricity. In the relatively recent years, the United States' energized power grid market has had a drastic change in competition, preventing increase in consumer prices and providing energy security independence in the first time since the world war. This market change was a direct result of new technology, obtained by the long-standing natural gas industry, just as experts awaited market failures as a result of oil production impacts. (Yergin, 2020)

In this study we are exploring how the potential of Offshore Wind Energy in the Mid and North Atlantic, and how new installations might be affected by policies regarding risks from natural solar weather events.

In recent years, the offshore wind industry has stood out as one of the most promising renewable energy solutions worldwide. In the United States power market, an extraordinary potential exists off the East Coast. Especially in the North Atlantic region, the market has been in recent competition between coal and natural gas. The new source of energy in this region could have significant impacts on the reduction of CO2 emissions and provide the United States, and the world, a very big step towards positive climate change mitigation.

If transmission solutions for Offshore Wind collaborate and build out a larger, more robust HVDC grid network to mitigate risk for solar weather events, there are potential bipartisan relationships where resiliency solutions will be created for human-related threats identified in importance by both political parties.

Background.

The new energy market

In the early 2000s, an individual persistently pursued a notion that oil, and natural gas molecules could fit through pores in rock formed from the intensive drilling process. After verifying size comparison in old boring logs in the Eagle Ford Shale in Texas, he was able to partner up with the recent advancements of the horizontal directional drilling (HDD) technology to establish a new hydraulic fracturing process to access natural gas. (Yergin, 2020)

This new process resulted in substantial increase in quantity. A single company now measuring quantity in trillion cubic feet (TCF), where up to then would be in billion cubic feet (BCF). In 2012, the first HDD well in the Permian shale region of Texas was drilled. By 2014, Permian output raised to 2 million barrels, 25% of US crude oil. (Yergin, 2020)

Natural Gas regulation on emission led to innovation, despite the vast reservoir of natural gas. The power sector developed further processes in the combustion process to improve efficiency, channeling the output that would further global warming impact back in to the cycle to produce more power. The efficiency improved capacity factor, output and furthered the gap of competition in the energy market in favor of natural gas. Coal, nuclear and even other renewables could not compete.

The HDD industry found a way to bring fuel closer to the consumer, by pipeline. Natural Gas could place moderately sized power plants closer into communities, where other sources, such as coal, could not. This was clear as the new administration in 2016 tried to sway the market in favor of coal, where according to reports, having spent more than $1 billion dollar of taxpayer funds into the industry. As one source puts it, "Trump Didn't Save Coal or Steel. To Be Fair, No One Could" capturing more than a 30% decline over only four years. (Nocera, 2020)

Had the power system transmission losses over the vast distance between coal and the consumer been less, some of this market offset impact would have been improved. Transmission experts are considering these losses as they suggest a new means of energy transmission for future types of energy.

Another route in this new energy market was established as the natural gas industry wielded its new technology and processes, taking control of the competitive market. The prior administration during this era released a "vision to cut carbon pollution and transition our country to a clean-energy economy" but invested in to planning efforts in collaboration instead of challenging the natural gas industry, by "Establishing a White House Interagency Working Group on Offshore Wind". (Office of the Press Secretary, 2015)

The collaboration efforts evidently seem to reflect they will pay off in the near future energy mix. The offshore wind energy yields capabilities and new technology solutions that are presenting cost-effective access to vast quantities of power and lower costs. The potential of this energy source has benefits to solve existing issues and provide for a new market competitor, but the challenge of transmission still exists.

Offshore Wind as a competitive source

As the natural gas industry was emerging from their new technology and processes, another event occurred, causing a substantial impact on the future energy market. In 2010, BP's Deepwater Horizon Oil spill recorded the largest accidental oil spill in history. This devastating event led to the creation of Bureau of Ocean Energy Management (BOEM) and $65 billion in compensation on the impacted public, primarily US residents in the gulf. (BOEM, 2020) The role BOEM was assigned would also be responsible for the allocation of "blocks" or leasing areas where offshore wind farms could co-exist amongst the many stakeholders using the resources of ocean territory of the United States and its states.

Clashing between politics and powerful market players invested in the oil industry led to a substantial overlap between politics and market strategy, by means of donors and think tanks. From one of these think tanks emerged an economist who presented an opposition to wind as a competitive source. In 2014, John Lesser on behalf of the Heritage Foundation, called for congress to eliminate subsidies for renewable and smart grids, eliminate FERC 1000, an order for collaboration among power providers and improve resiliency and recovery of the power grid. (Lesser, 2014) This economist demanded that the government reduce policies for environmental standards, build communication silos and then tell the utility transmission owners and operators to identify their own risks. "Congress should eliminate these subsidies and implement market-based reforms that will truly improve the electricity grid's efficacy and resiliency." (Lesser, 2014)

This political motivation was in direct conflict with the collaboration efforts of the administration, naming "working groups" designed to "focus on sharing lessons learned, discussing regulatory approaches and best practices, and exchanging scientific and environmental information". (Office of the Press Secretary, 2015) . Lesser's argument suggesting elimination of communication plan strategies targeted FERC 1000, a mandatory collaboration requirement amongst stakeholders.

However, Lesser also captures the importance that such communication needs to take place. He states, "rather than implementing one-size-fits-all federal standards, utilities and transmission system operators should be able to work together to identify risks and appropriate strategies to address those risks" (Lesser, 2014), suggesting that the "market-based approach" requires less government involvement. By pushing back on agencies, these think tanks and donor controlling mechanisms successfully influenced a mindset that considered a line in the sand between wind energy and its potential as a competitive market source.

The wind industry grew considerably as a renewable energy, but still minimal in relation to natural gas. However, similar to the rise of the natural gas industry, wind has been rapidly advancing in its technology and construction processes, addressing issues with more efficient solutions. Issues such as the NIMBY phenonium, migratory bird impact, and land availability have pushed wind power solutions capable further offshore and larger in size. These improvements are drastically increasing supply and lowering the capacity factor, which, without a cost associated with fuel, is lowering consumer cost.

The Wind Outlook 2019 evidently captured the sensitivity to free-market based approach, highlighting worldwide "zero-subsidy tenders" being awarded. The report does not leave solutions to debt financing solutions, however noting that "commercial banks are now more comfortable with offshore wind projects". The cost of equity has evolved as well, "with lower perceived risks from investing in offshore wind assets being underpinned by supportive policies" which "has led to some recent auctions being able to take place without any government subsidies". (IEA, 2019)

Policies along the way did help, and Offshore Wind will enter the market as a competitive source, as long as it overcomes other hurdles, physical and political. The IEA report states, "Innovation is delivering deep cost reductions in offshore wind, and transmission costs will become increasingly important", suggesting that "direct current technologies" or HVDC will have an important role. (IEA, 2019)

The Potential of Offshore Wind Energy

In recent years, the US offshore wind industry has been able to capitalize on innovation which has come from investments in the US as well as around the world, especially Europe. The recent "Offshore Wind Outlook 2019" outlines in detail how the energy source has the potential to meet global energy demand. Estimates referenced that the industry is expected to increase by 15 times, in to a $1 trillion business, by 2039. Of that potential, a technical potential of 46,000 TWh per year lies in the United States territory, of which only about 25% or 11 TWh per year are in the continental United States (conus). (IEA, 2019)

The outlook states that the US shallow waters have the potential to support 3,300 TWh, but in deeper water another 8,700 TWh exists, noting that some is located near major cities Washington DC, Boston and New York. This potential is the target area we are exploring in this study.

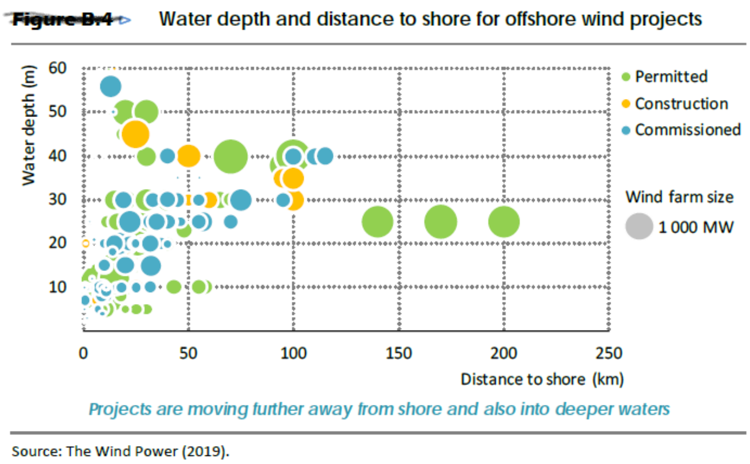


Figure 1 Water Depth and Distance to Offshore Wind Projects

New advancements, such as floating offshore wind platforms, have the potential to reach depths greater than 60 meters, or roughly 200 feet deep. Figure 1 reflects the water distance, and depth, to offshore wind projects captured in the IEA report. (IEA, 2019)

From this, we see that most of the installations exist within 50 KM, but there are several projects permitted for far reaches up to 200 KM, or 124 miles, to shore.

Offshore Wind Infrastructure: HVAC or HVDC?

The US department of Energy, Office of Electricity Delivery and Energy Reliability states “HVDC is a key technology in overcoming problems with renewable generation like wind, solar and hydro – that these resources are seldom located near the population centers that need them”. (US Department of Energy, 2017) However, the existing US power grid is almost exclusively an HVAC network. To understand why that is, we must go back to the early “planning effort” between the original market competitors originating in the 1880s. This early evolution of the energy market is often referred to as the “War of the Currents”.

Innovations by either Nikola Tesla or Thomas Edison could have shaped the power grid as we know it today. As the history states, neither inventor truly won, as Nikola Tesla sold his patent on alternating current induction motors to Westinghouse who built their empire with the United States power infrastructure based on the HVAC model. (Nix, 2019) If Nikola Tesla had the semiconductor technology we have today, perhaps the grid would be HVDC and serving another path which many experts identify as a more effective solution for the US grid as we know it. But even if the stepping technology were available, early grid competition would have had to yield to a planning effort with the consideration of other competitors and consumers over longer distances, an unlikely feat in the early unestablished energy market.

As a generator, the wind turbine produces AC currents, so if it were not for the longer distances needed to reach the grid an AC solution would be more effective. However, since the offshore wind farms are inherently so far from grid tie-in points, the vast distance exploits the advantage that HVDC has in power line loss per length. Although natural wind is "free", the reduction of these losses still allows a higher percentage of the generation to reach its target and therefore making better use of initial investment, aka up-front costs, of each development project. This along with all the other percentage-based impacts on the delivery of power generation from the turbine is called a capacity factor, a measure used to level out the competition over grid usage with other power sources.

Other power sources on our grid are generally AC power generation, just as the wind turbine, however usually with additional steps, or processes, along the way. Combustion type generation, such as natural gas, nuclear or diesel generators, all require a phased cycle approach effort to create electricity, including a combustion process, a power generator and means of cooling. The fuel required for combustion requires fuel, often associated with transportation, mining and/or drilling and the cooling requires a significant heat exchange, which is often handled by water. Utilization of these inputs/outputs for the additional processes has had a negative effect on global temperatures, creating long controversy in their "fair use" in a fair competitive market. Access to the natural resources is another factor, often continuing the effect on global temperature, while also establishing a variable production cost.

Management of Risk to the Power Grid

Risk and resilience are sometimes bundled together in error as a common challenge but are very different. Risk, a management category, can consist of positive or negative risks, which are measured. Resilience is the ability to return to a normal condition after being compromised by an actual event. Design for resiliency would assume that an event will ultimately exist, providing the mitigation strategy.

When it comes to Wind Energy, there are many challenges, or risks, such as land availability, intermittency and policies set to prevent impacts to birds or plane routes. A study in 2014 captured early on how offshore wind energy has the potential to overcome these challenges, but would face a new, greater challenge: "the transmission of large amounts of energy over long distances". (Raymundo Enrique Torres Olguin, 2014)

In terms of Offshore Wind Energy and its supportive infrastructure, resiliency to solar weather is highly dependent on the size of the solar storm we plan to address. As the transmission increases in distance, the impact from any solar storm will increase, as the impact is measured by a voltage per unit length. To be resilient to each event, the power system must overcome the charge impact and return to its original operational state, as soon as possible – if not immediately.

Furthermore, as the solar storm increases in size and intensity, the probability decreases; no different than the risk associated with a hurricane. Regardless, to be resilient would consider the event of the worst-case scenario storm event possible, which will require an understanding of what a Coronal Mass Ejection (CME) is and how bad it could be for a future power subsea cable.

The Risk associated with Solar Weather

Recent science and technology advancements, particularly by satellites, have drastically improved our understanding of the sun-earth interaction and the changing climate that the world population is experiencing. One part of this interaction is in solar weather, and what risk may exist from its impact on to Earth.

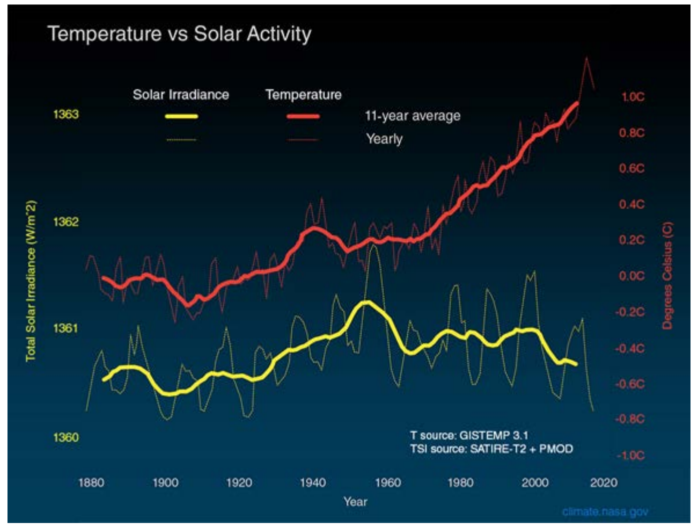


Figure 2: "Space Weather Effects on Climate"

NOAA presents one consideration of "Space Weather Impacts on Climate", suggesting that cosmic rays from the sun could possibly be seeding cloud formations and creating cloudier conditions, but should not be taken out of context regarding its comparable effect to influence from the industrial period. ((NOAA) NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, n.d.) However, it recent years it has become quite evident that climate change and solar weather impact are two entirely separate risks due to the level of magnitude of the threat of rising global temperatures since the 1960s, as reflected in figure 2, from the NASA website, on their website "What's the sun's role in Climate Change". (NASA, 2019) Another source from the agency, NASA Global Climate Change, addresses potential confusion clearly in the following statement:

"The amount of solar energy that Earth receives has followed the Sun's natural 11-year cycle of small ups and downs with no net increase since the 1950s. Over the same period, global temperature has risen markedly. It is therefore extremely unlikely that the Sun has caused the observed global temperature warming trend over the past half-century." (NASA Global Climate Change, 2020)

As NASA and NOAA continue to closely monitor the sun-earth relationship, they have recovered data reflective of another risk caused by a solar weather event on the sun, which is called "Coronal Mass Ejection" (CME). These CMEs are caused by an explosion of energy from the sun, which may be frequent based on where the sun is in its own solar cycles. The risk caused by these CMEs has a very low probability of impact, however, if not mitigated the impact has the potential for extraordinary devastation to our nation's power grid.

Generally, the Earth's magnetic field and atmosphere provide protection from the solar wind. However, the magnetic structure of a large CME can interact with the Earth's magnetic field in a way that allows charged particles to bombard the atmosphere while also rapidly altering the geomagnetic field in a way that significantly impacts human life.

Before modern infrastructure existed, humans would have only considered a GMD for its natural beauty in the form of an aurora, as there were no long cables to accept the magnetic charge induced through the coupling of the charged atmosphere and Earth. The first major CME to occur after human infrastructure existed is known as "The Carrington Event", which happened in 1859, over 20 years before electrification. The CME brought havoc on to the nation's telegraph system, by energizing the thin communication wires which were no match for the induced power from the sun's electron burst.

Had such an event from the sun occurred more recently, the impacts would have been devastating. Although the power cables used for transmission are much larger than the telegraph wires, the network has grown to span great distances and in the United States, is often near or at capacity. Major charging of our power infrastructure is a notable threat, and in 2012, a near miss obtained the attention of politicians.

Policy Regarding Geomagnetic Storms

In 2015 the TPS-007 mandate, was ordered to address the GMD threat by means of a mandated collaboration effort, in a phased plan. TPL-007-1 specifically to identify the risk, establish benchmarks, establish a mitigation plan, and deploy. This collaboration effort put scientists together with transmission operators and agencies, such as FERC, to deploy rules necessary to protect the public. (Frank Koza, 2017)

However, in order 830-A in 2017, FERC standard TPL-007-1, consisted of disputes and overlooked objections, which suggests that such communication efforts originally planned for were not effective. Political oppositions argued that FERC releases undermined the appropriate risk level that is appropriate for a mitigation standard. (Thomas Popik, 2017) The report stated:

"In the analogous case of Standard TPL-007-1, if the Benchmark GMD Event were to be set at the maximum threat level that had been estimated by the respected space weather scientists previously engaged in the NERC standard-setting process (30-40 volts/kilometer), many transformers might need hardware protection. Instead, the NERC Standard Drafting Team, consisting all of industry representatives except for one scientist, downwardly averaged the Benchmark GMD Event to 8 volts/kilometer. And instead of using maximum readings of geomagnetic disturbances recorded in the United States, the NERC standard-setting team opted to use averaged data from Northern Europe over a limited time period lacking any major solar storms." (Thomas Popik, 2017)

Through the mandated collaboration effort of TPL-007, additional phases were established to provide guidance documents.

The TPL-007-1 standard identified that having backup transformers across the grid was an essential resolution strategy to GMD impacts. This strategy reflects that grid owners will accept the risk, assuming it will occur, rather than mitigate the risk by investment into the infrastructure capacity issues. The fact that solutions came to this conclusion speaks to the quality of the state of the infrastructure of our nation's power grid. Having a redundant backup transformer will come at a high up-front cost, likely unrecoverable as sunk investment, and will also require routine maintenance to assure it is functional in the event it must be installed. The LIFT Act, a proposal not ratified, considered continuance of funding to address resiliency solutions for the grid, noting both solar weather and the lesser EMP as potential threats. Its focus was to be towards the transformer replacement program determined in the standard, however, it was supported by only one party and did not get ratified.

While the LIFT Act remained unaddressed, the “Executive Order on Coordinating National Resilience to Electromagnetic Pulses” was executed on March 26, 2019. This order was directed at Electromagnetic Pulse (EMP) or High-altitude EMP (HEMP) attacks from nuclear detonations in the atmosphere, noted as “approximately 40 kilometers or more above the surface”, which would require an attack from another nation. The order compares the threat of an EMP as an equal counterpart to a natural GMD from solar weather events, claiming that “both HEMPs and GMDs can affect large geographic areas”. (Executive Order on Coordinating National Resilience to Electromagnetic Pulses, 2019)

The comparison between HEMPs and GMDs within the same scale is considerably inaccurate, as a HEMP would be limited to a metropolitan area, where a GMD originates in the North Pole and generally engulfs entire sections of the planet. For example, the Carrington Event was reported to have stretched from the North Pole all the way to Venezuela, making this a global threat. The executive order misleads mitigation requirements by only acknowledging the requirement to addressing the EMP risk, setting aside GMD, which limits solutions which would provide for offshore wind infrastructure which would not fall within the threat area of an EMP. Some experts point out that if a nuclear detonation at these altitudes were large enough to be a nationwide threat, the risk associated with the nuclear blast would far outweigh the effects from geomagnetic disturbances. Nevertheless, the risk is identified, and this study captures both in the consideration of the larger GMD risk.

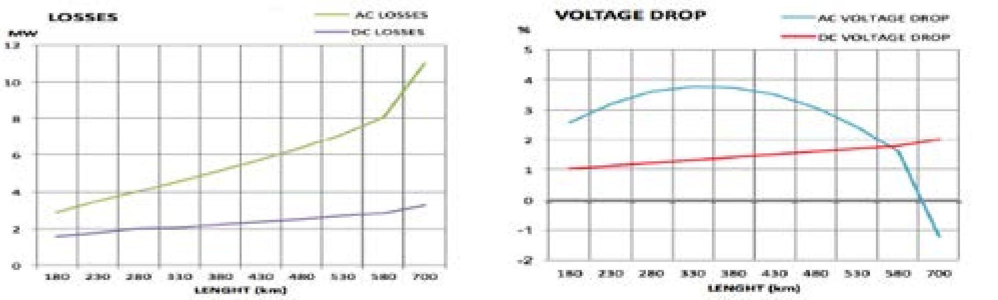
The LIFT act was not limited to the need for the power infrastructure to address solar weather events or geomagnetic disturbances, it also addressed climate-related risks as well. It also included proposals to address global warming mitigation. The basis behind the LIFT Act is a dire need “to rebuild and modernize” the US power infrastructure, which has been a bi-partisan concern. Ironically, when it comes to these threats, some are a result of human activity, such as EMPs, some are purely natural events, such as solar weather events, and in the case of climate-related events, a result of a combination of both human and natural changes.

Power Grid Resiliency

Physical challenges will increase as the distance from the shore increases to capture the greater potential of offshore wind power available, as previously mentioned from the Offshore Wind Outlook report. We captured previously that solar weather events will increase linearly, as the impact is measured in voltage per unit length, but this should also be known to be a physical constraint on top of another key issue – which is the voltage drop per length, which is not quite as linear. To capture the amplified impact within this analysis, I use the findings from a 2019 report, “Comparative Study of HVAC and HVDC Transmission Systems, With Proposed Machine Learning Algorithms for Fault Location Detection”.

The report by Bassam Albannai provides data for the losses and voltage drop over extended lengths, as a percentage of the flow. As defined in the study, “voltage drop is the amount of electricity wasted due to the resistance of the transmission line”. (Albannai, 2019) To account for the variability for those losses in the analysis, we utilized Albannai’s data reflective of a ‘typical’ loss per cable. Albannai plots his data as shown in figure 3.

Figure 3: Visualization of Data Points



(a) Losses in AC and DC Lines (b) Voltage Drop Across AC and DC Lines

"Comparative study of HVAC and HVDC transmission systems" by Kalair et al, identifies a comparison to HVDC and HVAC, which has findings that reflect that HVAC would require 2:1 cables to carry the same capacity in MW. The study states "A 66 kV 5 km long 3-phase AC line has the 87 MW power transfer capability, whereas a 66 kV 5 km DC line can handle up to 167.6 MW which is 1.925 times more than an equivalent AC line". It references an "equivalent" HVAC transmission cable system to the HVDC line consisting of an additional set of wires, as part of goal to fit inside of a common ROW (Right-of-Way). (A. Kalair, 2016)

The comparative analysis by Kalair, et all provides very well for land based transmission, however beyond the coastline of the US, the ROW would be less relevant, and the numbers of cables would increase the impact from a solar storm event considerably. For each additional wire, the HVAC system "equivalent" would double in impact.

Kalair et al explains that "In a typical HVDC system, the AC power is taken from AC network, converted into DC by a converter station and transmitted to remote point by an overhead line on land or submarine cable in sea". (A. Kalair, 2016) The is an overall explanation for the disadvantages to HVDC, for the purpose of this analysis are captured at a "break-even" distance of approximately 50 kilometers, where the costs associated with the additional equipment to convert for DC transport zero out with the savings per unit run. For the purposes of this analysis, all the subject location wind farms are beyond 50 kilometers, considering the assumption that from that point the other features are negated.

In investigating typical configurations, we find that HVDC systems also tend to install several wires to transport power, generally for redundancy. (ABB, 2006) This study assumes the same redundancy would not apply to the HVAC, and therefore assumes a single HVDC wire will be utilized.

The analysis in this study breaks down these multi-wire systems based on these assumptions, calculating 3:1 wire ratio for 33kV to 200kV power networks and excluding HVAC for power subsea cables for 400 kV and 525 kV networks, where the systems would require too many wires to be feasible in resistance to GMD. Where the power lines would be subject to permanent damage in the event of a solar weather event, TPL-007 would require a backup transformer. Here, we assume a backup transformer is not a feasible solution for an offshore wind substation.

The risks from natural atmospheric weather will be substantial to the offshore wind market but may be avoided with longer HVDC transmission runs capable of tie into multiple network points on the grid. The risks from geomagnetic storm disturbances will grow, however, the risk from EMP threats will decrease.

Many experts have exposed a critical opportunity for offshore wind industry, in how it will benefit from the advantageous use of HVDC, where traditional HVAC transmission has dominated the grid, because of it is length. To this point, the HVDC transmission solution could potentially reach vast lengths across the country, connecting different regions as they face different natural disasters caused by climate change. However, vulnerability to geomagnetic disturbance, as well as EMP often is omitted from planning efforts because it has been relatively silent in politics until very recently, when a "near miss" occurred in 2012.

With our modern infrastructure, the 2012 near miss would have caused trillions of dollars and potentially left many of the United States without power (NASA, 2014) as the population scrambled to build long-lead transformers to replace those that would have inevitably fallen to the power surge of over 20V per linear kilometer of transmission line. Lower latitudes and independent grids, such as distributed renewable systems and all of Texas, would have likely avoided the catastrophic impact. However, much of the United States power grid would have suffered impacts that would affect major essential parts of our society even beyond the average consumer, such as hospitals and national security. Although the probability of an extremely large CME directly hitting the Earth is very low, that fact is that "we need to be prepared" as explained by NASA scientist in response to the near miss in 2012 (NASA, 2014). Ironically, only those with solar roofs or wind turbines, along with substantial battery packs, would have avoided a trip back to a time without electrification.

By investigating long lengths potentially necessary for the offshore wind industry, partial resilience to hurricane events can also be assessed. While longer transmission runs are a hinderance for resiliency to solar storm events, it's impact to hurricane resilience is inversely affected. The longer a transmission run can travel West into the continental US, the lower the probability its tie-in point will be subjected to devastation from the regional storm events. Although the hurricane events are also rare, there are trends suggesting our future is to expect a high frequency as global temperatures rise.

Methods.

The study investigates Offshore Wind farms in the farthest reaches of the OCS, to best consider limiting factors of the future potential of the new technology. It first investigates two types of transmission distribution, HVAC and HVDC, in their resiliency against the risk of solar weather associated with length of runs. As a second part, the study will analyze the resilience potential to geographically avoid regional climate-related impacts based on the distance of the grid tie-in point.

Data & Assumptions

By analyzing the risk to transmission networks of offshore wind energy associated with solar weather, this study can assess the relative impact to a variety of resiliency objectives, not limited to the solar weather events. The primary objective in this study assesses resiliency to geomagnetic disturbances, which as mentioned previously, may be of various levels of severity and various types, which will be defined.

Also mentioned previously, the risk associated with solar weather will be inversely affected by risks associated with regional climate-related impacts: hurricanes, tropical storms, cyclones, and sea level rise. These risks will not be considered on the production side, where the wind farm would be potentially located. Modern technology advancements of the offshore wind turbines are overcoming resiliency issues associated with heavy storms, for example, turbine blades having “feathering” and “breaking” capabilities to adjust for excessive wind force.

Instead, vulnerability to these risks is analyzed at the grid tie-in point side, which could be at one or more locations. To perform the analysis, engineering and design considerations regarding the network configuration are necessary to understand what technical aspects of transmission grid tie-in points are applicable.

Transmission Configuration.

The risk associated with GMD has established its physical impact on unit length of cable installed and grid connection tie-in point along latitudinal lines of the Earth.

This study defines transmission configuration as the design factors applicable to the high-level planning process, specifically addressing length of cable and grid tie-in point. Engineering offshore wind farm transmission solutions is a complex process, yet without the challenges that are expected to be faced in the future as land blocks are used up. In a future energy mix that is utilizing a large portion of the potential of offshore wind energy along the East Coast of the United States it is expected that wind farms will push further out, increasing distance, and also compete with limited tie-in points along the shoreline. Amongst the most important elements of the high-level planning process is to collaborate cooperatively and build out a system planned for this future. (Brandon Burke, 2020)

The communication plan strategy for future planning considers policy and government agencies as discussed previously and is briefly discussed to identify assumptions associated with the risk assessed in this study. Furthermore, technical design factors include assumptions for the grid tie-in connection strategy, the number of cables along the latitudinal length and the current type (HVAC or HVDC) described previously.

Communication Planning, Collaboration & Partnering

This study utilized information provided by “Offshore Wind Transmission White Paper”, as authored by Brandon Burke et all, which is a publishing by the Business Network for Offshore Wind. The Business Network for Offshore Wind identifies themselves as a non-profit “dedicated to building a network that will usher the U.S. into the offshore wind market”. (Business Network For Offshore Wind, 2020)

The members of the offshore business network found that transmission coordination efforts have been reactive to transmission requests, where better planning efforts would consider the future needs. FERC 1000 requires that meetings amongst the transmission stakeholders will take place to tackle such coordination efforts. The paper suggests that the DOE and FERC could also partner up to solve this area by playing "a critical convening role with stakeholders across states and RTOs". (Brandon Burke, 2020, p. 39)

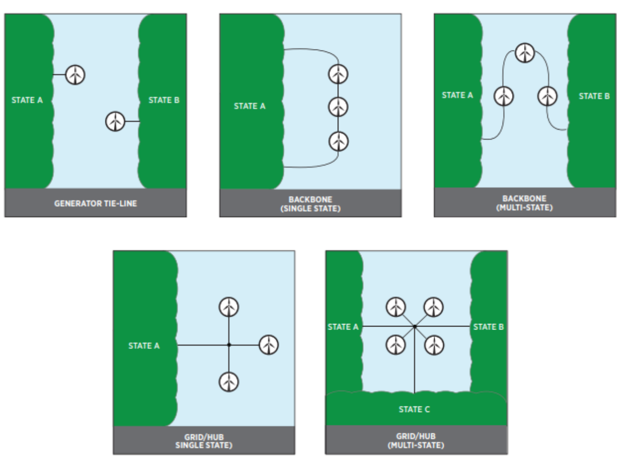
Such a coordination effort would be challenged with the task of crossing state lines but may find opportunity in addressing a "common enemy" in extreme risks resulting from solar weather activity, hurricanes, or other natural disasters subject to more potential frequency as a result of climate change. The basis of this study explores the most extreme risks that may be either a hurdle to overcome or a solution to address, depending on how far the transmission reach.

Offshore Grid Connections.

This paper demonstrates two primary core solutions for the means in which Offshore Wind Energy may tie into the grid. These configurations are essential to understand when associating length of cable

The first is a "a generator tie-line transmission configuration", where each wind farm would have its own dedicated grid connection infrastructure and the second is a network approach. The author explains that "in a shared network transmission model, multiple OSW installations are connected to shore via one or more shared offshore substations and export cables (often, but not always, utilizing direct current [DC] technology)". (Brandon Burke, 2020) Figure 4 from the white paper reflects a generator tie-in and various ways to work in a shared network model.

Figure 4: Offshore Wind Transmission Solutions



This study investigates the two general methods described for grid tie-in, as well as the potential for taking the shared network transmission approach a step further, say type 3, into its own independent transmission system inland. Type 3, as discussed in an open source podcast discussing the white paper release, reflected a feasible potential to limitless bounds westward in its own network, however, might not reflect good "relationships" with existing operators. (Burke, 2020)

Where the white paper states that "currently, there is no entity responsible for considering transmission needs for the overall build out of offshore wind on the east coast", this study considers the potential for larger offshore wind to possibly serve as an independent system crossing RTO and/or ISO boundaries. (Brandon Burke, 2020)

One consideration that is considered by Burke et all is that the tie-in points along the coast may not be available to future power stations if the transmission network is developed on a first come first serve basis. Where the Wind Outlook 2019 noted that the resource potential is in the vicinity of New York, DC, and Boston, the findings in this white paper write “Along the U.S. East Coast, OSW resources are located in relatively close proximity to load centers, but most OSW lease areas are distant from optimal points of interconnection to the existing onshore transmission networks.” (Brandon Burke, 2020)

This study considers that these potential “distant optimal points” are also captured by concept in analyzing two different case blocks for reaches beyond Hurricane zones only to the farthest reaches. Although it is expected that offshore wind farms in the distance future will likely remain considerably closer, the lesser distances would still be applicable for the purposes of this analysis. Therefore, the analysis would be considering “worst case scenario” and rational break points in between.

Current Type (HVAC or HVDC)

The US department of Energy, Office of Electricity Delivery and Energy Reliability states “HVDC is a key technology in overcoming problems with renewable generation like wind, solar and hydro – that these resources are seldom located near the population centers that need them”. (US Department of Energy, 2017) However, the existing US power grid is almost exclusively an HVAC network which was explained previously in the background section of this study.

HVAC

As a generator, the wind turbine produces AC currents, so if it were not for the longer distances needed to reach the grid an AC solution would be more effective. However, since the offshore wind farms are inherently so far from grid tie-in points, the vast distance exploits the advantage that HVDC has in power line loss per length. Although natural wind is “free”, the reduction of these losses still allows a higher percentage of the generation to reach its target and therefore making better use of initial investment, aka up-front costs, of each development project. This along with all of the other percentage based impacts to the delivery of power generation from the turbine are called a capacity factor, a measure which is used to level out the competition over grid usage with other power sources.

The HVAC solution requires a step-up transformer prior to the long transmission of power, where it then needs a step-down transformer prior to its functional use by the public. Both of these transformers are vulnerable to geo-magnetic disturbance (GMD), which has a charging effect on the long lengths in between.

Lastly, HVAC requires multiple phases. These phases result in magnetic disturbance on marine life, and a slight heating effect, which are not considered within this analysis. The more relevant factor to this study is in the number of separately coupled wires, which is covered in the number of cables below.

HVDC

The benefit of converting the rotational energy produced by each wind generator to DC current is in the losses of the longer run. For this reason, there exists a break-even point for HVDC in terms of cost and length of run. According to a study, the break-even distance is found to be much smaller for sub-sea cable systems, roughly 50 - 80 kilometers (30 - 50 miles), than that of overhead systems at 400 – 700 kilometers (250 – 430 miles). (Albannai, 2019)

This study does not analyze cost breaks; however, the break-even distance is valuable in determining the relevancy of measuring the use of HVAC solutions and assessing results. Figure 5 to the right represents these high-level assumptions.

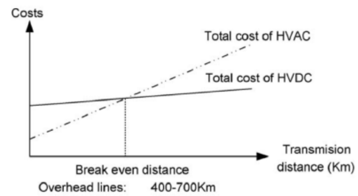


Fig. 1.11. Costs of AC and DC Overhead Lines Based on Distance [20]

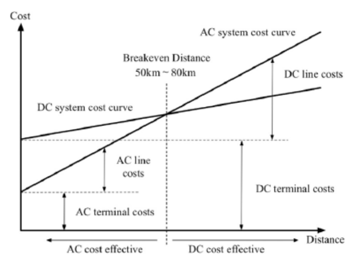


Fig. 1.12. Costs of AC and DC Underwater Cable Based on Distance [21]

Figure 5: HVAC vs HVDC break even costs

Number of Cables

The United States power infrastructure on the East Coast is also falling vulnerable to the changing climate impacts, but because of atmospheric weather, flooding, and sea level change instead. As result of the "war of the currents" and a history of competition over existing transmission cables, the Eastern United States power grid consists of a vast network of overhead lines facing capacity challenges. A better planned network would have consisted of larger capacity lines and below ground solutions far less vulnerable to the elements and weather events. As a result, power grid operators have valued extremely inefficient and costly peak power solutions in acceptance of the climate risks, as opposed to better quality solutions which would potentially mitigate.

A means to address these issues is in providing redundancy in the cables, or more cables per run, which leaves opportunity for growth and a continuance of large portions of the power in the event of damage, maintenance, or other similar scenarios. This general engineering comes at a higher cost, but also provides substantial resiliency to a wide array of threats. However, when considering resilience to geomagnetic disturbances, more cables can potentially worsen the impact, and therefore increases the susceptibility to the risk.

Noting that GMD is defined to a voltage per unit length, each additional cable for redundancy or necessary because of capacity, as for HVAC systems, will be subject to its own linear impact.

A HVDC cable run may be of a variety of types, such as monopole (1 wire), symmetrical monopole (2 wire), bi-polar and multi-terminal (MTDC), which is noted as the most used. To simplify this design consideration for the purposes of this study, HVDC systems are limited to the maximum capacity of a single core subsea cable, as shown in the figure 6, as provided by ABB. (ABB, 2006)

A general HVAC three phase transmission has three applicable wires, which are not uniformly coupled. These three wires are generally separated on overhead runs; however, a single subsea cable would require an insulated core to prevent the coupling of the different phased lines. Since these phases are not coupled, these are still affected as three separate wires, as shown. (ABB, 2006)

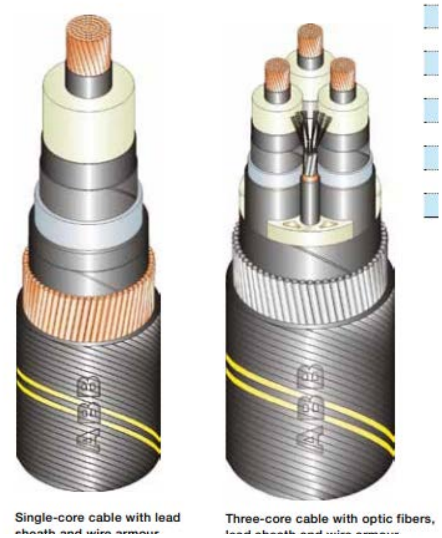


Figure 6: Physical Cable View, HVAC vs HVDC

Having three separate internal wires per run, the HVAC cable is subject to three times the influence by geomagnetic disturbances coupled between the atmosphere and the Earth. This study accommodates this factor, however, considers that redundancy would equate out.

In more detailed engineering analysis where redundancy would be higher, each level of redundancy would be a factor of three, so exponentially great. In this consideration, larger HVAC cable systems above 200 kV, which require additional redundancy, are excluded because the engineering would require complexity beyond the intent of this study.

All comparisons in this study are factor based, considering the three to one ratio. In utilization of this study for redundancy, the analysis appropriately utilized for GMD resiliency would simply consider the impact as divided to each cable for larger MTDC systems providing for very large offshore wind farms of multiple connections in land.

Risk Selection.

Geomagnetic Magnetic Disturbances (GMD), aka Geomagnetically Induced Currents (GIC)

Regarding the longest transmission runs feasible, as mentioned previously will be of HVDC type, the biggest effect from natural forces will most likely be from the sun itself.

As mentioned previously, the risk to our nation's transmission infrastructure has become increasingly more visible with respect to the potential devastation which could occur as a result a geomagnetic storm and the piggyback risk of Electromagnetic Pulse (EMP). This study will explore different gauges of the risk, identified by the direct force which would be applied to the network configuration for future Offshore Wind Farms.

The more common geomagnetic disturbances from solar weather, as well as a GMD from a major EMP attack, would both typically be limited to a general location. Solar weather influence originates in the poles of the Earth, with the potential to stretch closer to the equator depending on the size or how extreme the solar event. An EMP attack would likely be near a city, and inland, but not have the capability to reach planetary reach as the case with solar weather without having much more devastating concerns from the nuclear explosion itself.

The study builds on this principle by calculating the minimum touchdown points on the mainland and assessing how much further the operational length can feasibly be regarding threats associated with geomagnetic storms. In capturing the overlay between geomagnetic storm and tropical storm threats, this study will provide valuable information regarding to the potential for using HVDC transmission during these natural weather events.

In previous investigations, it was found that there is much larger impact from geomagnetic storms near the coastline and more threat to HVDC lines. The coastal areas are reported to be as much as 20% greater during the same storms. The increased threat to HVDC systems is a result of its natural longer system runs, but also in consideration of more cost for the conversion equipment from alternating currents, which Offshore Wind Energy must utilize at the generation side as well as to tie into the existing HVAC network of the United States.

“During the 1989 geomagnetic storm, significant voltage fluctuations were noted in undersea cables — Application of modeling techniques have also been successful in validating voltage measurements on undersea cables” (Metatech Corporation, 2017)

1. Other Factors:

- “From a protection point of view, using pipes or armored power cables will not reduce the coupling” (Metatech Corporation, 2017)
- “Modeling techniques for undersea cables have been developed and have been validated against actual geomagnetic storms” (Metatech Corporation, 2017)
- The largest geomagnetic storm hit, 1859 Carrington Event, was prior to the development of the human electrification infrastructure. A recent “near miss” in 2012, would have been a larger impact, however, missed the Earth due to timing of the rotation of the sun. Such an event may occur in the future.

- "Previous calculations assumed a non-varying geomagnetic field over the entire length of the cable", but "In reality an electrojet storm magnetic fields will vary over thousands of kilometers" (Metatech Corporation, 2017)
- TPL-007 congressional mandate has pushed towards creating a plan and solution in a phased approach. There is a strong consideration of "standby" transformers to resolve the matter, rather than build the infrastructure in a manner resilient to the impact. This reflects "accepting" the risk, rather than mitigating it.
- The cost of a standby transformer would be much more impactful to an offshore wind facility, especially one of further distance out, and the installation time would be substantially greater, especially during winter months.

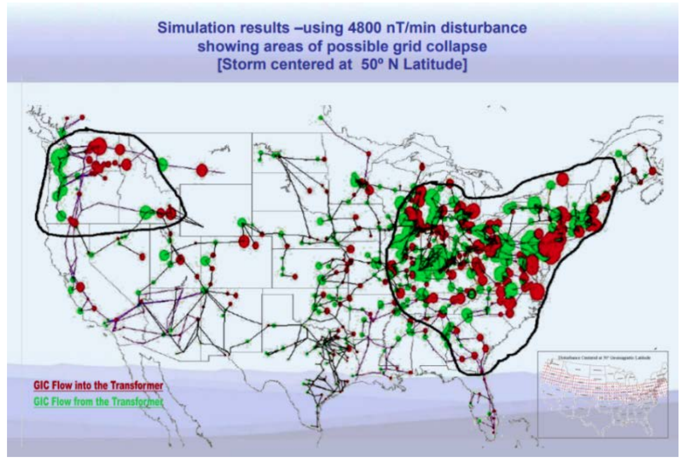


Figure 7: US Grid Vulnerability to 4800 nT/min Solar Storm

The impact of geomagnetic storms on the US grid will increase substantially towards the North, but major storms have a potential to pose a threat across the entire East Coast. The worst-case scenario typically assessed by the space weather community is 4800 nT, which would have a variable impact stretching the entire region. From a report in 2010, the vulnerabilities to such an event on the United States grid are shown in figure 7. In the same presentation, it was noted that the highest measured magnetic field, in Sweden, 1921, was 20 V per km resulting from a storm approximately 5000 nT in size.

However, in 2010 when this presentation was considering a risk comparable to the famous "Carrington Event" in 1859, as the Earth had not yet witnessed the near miss in 2012. One study providing the data regarding the 2012 event provides data as to how big the event could have been and provide considerations for future planning for the purpose of this study.

More recently, as our power sources have explored offshore opportunities, experts have been noting that there would be an expected coastal effect causing increase in geomagnetically induced current (GIC). One study in 2018 quantified it: "Quantitative influence of coast effect on geomagnetically induced currents in power grids: a case study", provides a specific value of 23% increase of influence along a coast, and although the case study is in China, the scenarios investigated with HVDC apply to physical conditions of any coast. (Chunming Liu, 2018)

Climate-Related Natural Disasters.

In parallel to the effect from geomagnetic disturbances, the study explores effects from extreme climate related risk in the same manner of localized, regional, and national. In this concept, a localized impact would be coastal effects, such as sea level change and flooding, which can cause damage to localized environments and may capacity factor of offshore wind farms by imposing on demand.

A more regional effect would be a significant hurricane, which is the core weather event for this analysis. An extreme hurricane event can impose on vast areas and result in major damage to infrastructure, as well as demand users. This study's focus would consider the necessity to reach beyond hurricane zones, as to decrease the probability of impact to usage of the offshore wind farm.

Lastly, national risks consider conceptional distances in the event of any extreme circumstance. In the farthest reaches, the West Coast of California, such as the climate influence on major forest fire activity. A network solution that could stretch national reach with HVDC might provide potential opportunity to further utilize farthest reaches of offshore wind energy farms, as perhaps to be a backup plan to other solutions.

Analysis.

The analysis was performed utilizing AutoCAD Civil 3D to import maps from BOEM Madre Cadastre, DOE wind outlook 2019 and geomagnetic maps from NOAA. Maps were scaled into a uniform survey coordinate system to assure high-level, rational accuracy of general distances for a uniform comparison of the various subject investigations.

To determine to what extent a HVDC system is feasible for the farthest reaches of offshore wind energy in general, the impact from GMD was analyzed to various minimal tie in points on the shore. As available in the marine Cadastre national viewer, several layers were taken into consideration while determining the study region for investigation.

The “Offshore Wind Technology Depth Zone” identifies the clear areas which are already capturing commercial and pilot projects in existence. “Several pilot projects have been successfully demonstrated in the deep water zone (60 - 900m), with foundation types including spar, semi-submersible, and tension leg platform designs.” (Marine Cadastre, 2020) However, in the purposes of this study, we consider that the planning effort for long term, 100 year+ risks identified for analysis would not feasibly be limited to current technology depth zones, limited to 900 meters.

Map analysis.

BOEM maps as available on marine Cadastre, and professional recommendation were both considered to determine feasible marker points for analysis. The farthest reaches of the map reflect the 200 Nautical Map boundary, located in red.

Beyond this, the permit map provided insight of the farthest permitted area. Figure 8 reflects an example of potential impacts which would push Offshore Energy further out to sea, as previously discussed.

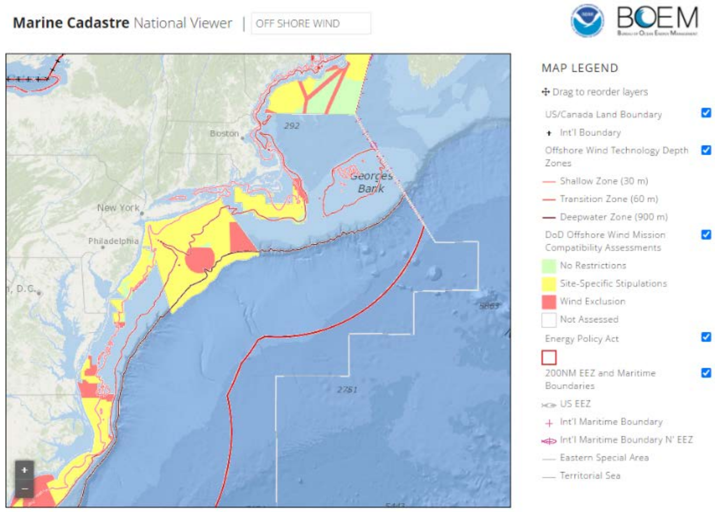


Figure 8: Coastal BOEM layers

Cable Selection

General sizes of subsea cables based on availability of major subsea cable providers were considered for feasibility in this assessment. To reduce complexity for the purpose of a high-level investigation, feasible subsea cables were confirmed as available to support with the fewest cables possible, and the consideration of MW capacity was omitted.

In further analysis, this study would be utilized in the engineering process while determining the capacity for each line, based on numerous factors considered to be outside of the scope of this analysis.

An example of cable selection sizes is reflected in figure 9, noting that these cables available in 2009 have been significantly improved upon. This array was obtained by a 2017 study which analyzed losses in subsea cables supporting offshore wind farms. (Jayasinghe, 2017)

Nevertheless, in this example, #5, the 450 kV subsea cable reflecting 600 MW on a single cable, would represent the most feasible use for resiliency to GMD for HVDC, as it does not require a cable pair such as #4. Notable in this array is the equivalent HVAC cable, #3, would be limited to 50 km, and require three cables.

Table 4. Five regular subsea cables types (Worzyk, 2009)

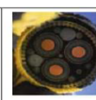
					
Cable Type No.	1	2	3	4	5
Rated voltage U_0	33 kV a.c.	150 kV a.c	420 kV a.c.	320 kV d.c.	450 kV d.c.
Insulation	XLPE, EPR	XLPE	Oil/paper or XLPE	Extruded	Mass-impregnated
Typical application	Supply of small islands, connection of offshore WTG	Connection of islands with large population, OWP export cables	Crossing of rivers/straights with large transmission capacity	Long-distance connections of offshore platforms or wind parks	Long-distance connection of autonomous power grids
Max. length	20–30 km	70–150 km	< 50 km	>500 km	>500 km
Typical rating	30 MW	180 MW	700 MW/ three cables	1000 MW/ cable pair	600 MW/ cable

Figure 9: Subsea Cable Examples

Jayasinghe's study provided findings that there were losses and restrictions in HVAC cables which generally prevented use in subsea cable lengths beyond 200 kilometers. The losses were also utilized to gauge break points for various bands of percentage impact on to the cable from GMD. Figure 10, from the study, reflects that generally cable losses are acceptable below 3%.

Figure 10: Cable Loss Example, HVAC vs HVDC

Power Loss %	Offshore Wind Farm Capacity: 500 MW				
Subsea Cable Length (km)	HVAC			HVDC LCC	HVDC VSC
	132kV:4 cables	220kV: 3 Cables	400kV: 1 Cable	400kV: 1 Cable	400kV: 1 Cable
50	2.26	1.0625	0.6125	0.22731	0.784315
100	4.17	2.355	1.675	0.24296	0.863502
150	6.8475	4.19	3.7475	0.25862	0.94269
200	10.315	6.725	13.9925	0.76047	2.021522
250	14.445	10.63	∞	0.80478	2.180745
300	18.5975	∞	∞	0.84909	2.338209

Benchmark Geomagnetic Disturbance (GMD) and impact rating system

The consideration for the assessment in figure 11 reflects a rating system for the impact from the geomagnetic storm on to the power grid system for the offshore wind power cables. This scale is derived from the impact assessment based on the severity of GMD, on a scale of G-1 to G-5 being the most extreme, which is shown in figure 12.

Acceptable	Inconsequential	0-3%
Manageable	minor	3.1% - 10%
Outage/Trip Risk	moderate	10.1% - 30%
Outage likely	severe	31% - 60%
Damage Risk	extreme	>61%
Damage will occur	unmanageable	**>100%**

Figure 11: Rating Scale for Analysis of GMD Impact

This scale is provided by 8V per kM geomagnetic storm is the planning range as identified to be the "benchmark", for a 1-in-100 year GMD event, per TPL-007-1 revision as of May 15, 2017. This GMD benchmark reflects the "calculated peak geoelectric field" according to the NERC standard.

Figure 12: Typical GMD rating criteria

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	**Extreme**	**Power systems:** Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** Pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).	Kp = 9	4 per cycle (4 days per cycle)
G 4	**Severe**	**Power systems:** Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** May experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** Induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	**Strong**	**Power systems:** Voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).	Kp = 7	200 per cycle (130 days per cycle)
G 2	**Moderate**	**Power systems:** High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).	Kp = 6	600 per cycle (360 days per cycle)
G 1	**Minor**	**Power systems:** Weak power grid fluctuations can occur. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).	Kp = 5	1700 per cycle (900 days per cycle)

The report also notes that there is an applicable factor adjustment for geomagnetic latitude, identified by the equation: $E_{peak} = 8 * \alpha * \beta$. Where α = factor adjustment for geomagnetic latitude and β = factor adjustment for regional Earth conductivity model. (Frank Koza, 2017)

The standard goes on to assess a "regional geoelectric field peak amplitude, E_{peak}, to be used in calculating GIC [GMD] in the GIC [GMD] system model" as a separate equation:

$$\mathbf{E_{peak} = 17^{*} \times \alpha \times \beta \qquad (V/km)}$$

In this equation, 17 V/km is based on a Los Alamos National Labs (LANL) report of August 2015, noting that this value would be used for a supplement assessment. Together, the calculation for GMD and supplemental GMD, are subjected to "local enhancement" using simulations of 100 km x 100 km blocks. For the purposes of this study, the severe risk is left to a consistent 17 V per kilometer.

These factors for GMD impact consider only inland threat, the report provides no offset for a near coastline factor, as mentioned previously in background research supporting this study. The coastal GMD effect is a 1.2 multiplier. (Metatech Corporation, 2017) This study assumes this potential phenomenon would only apply to GMD from major solar weather events, as the ground coupling would likely require regions too vast for a rational size EMP. Therefore, to account for this factor, this study limits the 1.2 multiplier to the severe benchmark analysis, capturing this as the general design risk for severe category, expectedly a G-4 category event.

The buried subsea cables may be several feet to meters deep, which may provide some degree of resistance to a HEMP or EMP attack, however, has no measurable effect on GMD resulting from atmosphere to Earth coupling from a major solar weather event. (Metatech Corporation, 2017)

To match TPL-007-1, this analysis also assumes a 60-degree North latitude reference location for calculations, therefore maintaining 8 Volts per kilometer as a "calculated peak geoelectric field". (Frank Koza, 2017)

Furthermore, as found in the background study, experts contested the benchmark analysis produced in the report, stating that the potential threat was substantially undermined. Noting that "if the Benchmark GMD Event were to be set at the maximum threat level that had been estimated by the respected space weather scientists previously engaged in the NERC standard-setting process (30-40 volts/kilometer)" (Thomas Popik, 2017) this study assumes that an extreme condition, referenced as a G5 event or greater on the scale, reflects a value of up to 40 V per kilometer. This study accepts the feasibility that up to 40 V per kilometer may be feasible as a worst possible case scenario under all circumstances, and assumes factors discussed previously have been accounted for.

The calculation was carried out further to add the necessary means to consider what is needed to extend past the tropical zones as captured in the BOEM layer, to see the minimum range needed to truly avoid initial natural weather impacts on the East coast. A last calculation extends the full potential of the HVDC lengths, in the consideration that it would be useful at all up to 85% capacity of the voltage rating. These two calculations intended to consider the extents of grid tie-in capability during a geomagnetic storm event, potentially supplementing other power types which may be less responsive to rapid ramping as offshore Wind.

Climate Related Impacts.

As the final part of this analysis, the mapping systems were utilized to find the potential reach for cable systems that are rationally resilient to GMD risk. For the purposes of climate-related risk, the BOEM layer of tropical cyclones in the North Atlantic was utilized, to determine how far west the probability impact stretched in terms of the length of additional cable length.

To accomplish this, two hurricane zones were determined, one at 250 NM and the other at 500 NM, to provide high-level analysis of the hurricane reach based on a potential grid point tie-in location, as discussed previously.

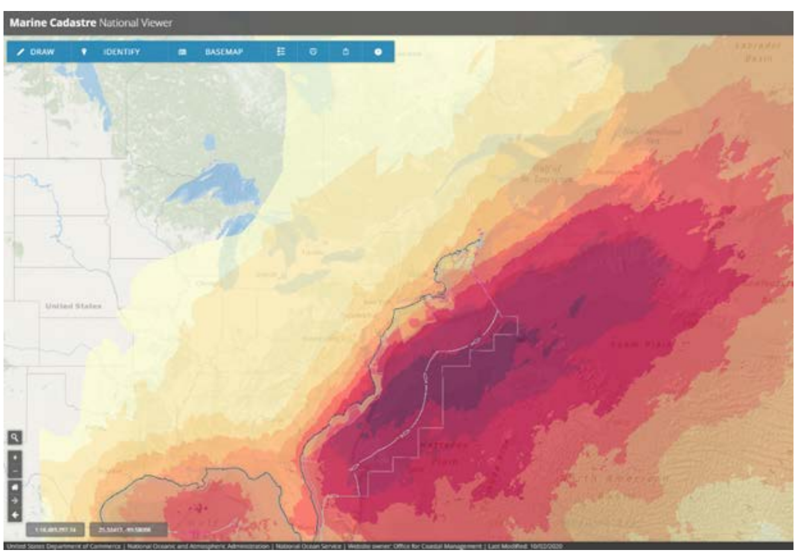


Figure 13: Madre Cadastre layer, North Atlantic Typhoon Probability

The map layer utilized clearly sets probability zones, declining as they stretch West into the continent. The concept in this analysis is to break the higher probability zones. The first zone, notable as the light shades of orange encapsulating Washington DC, is assumed reachable within the 250 NM mark, or a cable length, with a 15% error, of 287 miles (523 kilometers).

The vast area in the second to lightest region is considered past the probability associated with hurricane risk, obtainable with a reach of a cable length longer than

1000 kilometers. From the coastline, 500 NM generally reaches the center of the probability area, which accounts for over 50 kilometers out to sea. To avoid complexity, these assumptions do not account for increase in hurricane severity as offshore wind energy farms are potentially pushed further out to sea in the future.

Results

The analysis yielded the following data.

8 Volts per kilometer

Landmark Remark	Nautical Mile Mark	Surface Distance (km)	Distance (mi)	Aprx subsea cable L (kM)	Impact (V/cable)	% IMPACT 33KV HVAC (3 cable)	% IMPACT 33 KV HVDC (1 cable)	% IMPACT 132 KV HVAC (3 cable)	% IMPACT 132 KV HVDC (1 cable)	% IMPACT 200 KV HVAC (3 cable)	% IMPACT 200 KV HVDC (1 cable)	% IMPACT 400 KV HVDC (1 cable)	% IMPACT 525 KV HVDC (1 cable)	# occurences Tropical Cyclone (117 year)
Current Installations	25	46	29	53	426	3.9%	1.3%	1.0%	0.3%	0.6%	0.2%	0.1%	0.1%	60 to 80
Break-even AC/DC	50	93	57	106	851	7.7%	2.6%	1.9%	0.6%	1.3%	0.4%	0.2%	0.2%	60 to 80
HVDC significant	75	139	86	160	1277	11.6%	3.9%	2.9%	1.0%	1.9%	0.6%	0.3%	0.2%	60 to 80
Farthest Permit US	100	185	115	213	1702	15.5%	5.2%	3.9%	1.3%	2.6%	0.9%	0.4%	0.3%	40 to 80
Farthest Permit IEA Outlook	200	370	229	426	3404	30.9%	10.3%	7.7%	2.6%	5.1%	1.7%	0.9%	0.6%	20 to 80
Hurricane zone 1	250	463	287	532	4255	38.7%	12.9%	9.7%	3.2%	6.4%	2.1%	1.1%	0.8%	20 to 40
Hurricane zone 2	500	925	574	1064	8510	77.4%	25.8%	19.3%	6.4%	12.8%	4.3%	2.1%	1.6%	5 to 20

20 Volts per kilometer

Landmark Remark	Nautical Mile Mark	Surface Distance (km)	Distance (mi)	Aprx subsea cable L (kM)	Impact (V/cable)	% IMPACT 33KV HVAC (3 cable)	% IMPACT 33 KV HVDC (1 cable)	% IMPACT 132 KV HVAC (3 cable)	% IMPACT 132 KV HVDC (1 cable)	% IMPACT 200 KV HVAC (3 cable)	% IMPACT 200 KV HVDC (1 cable)	% IMPACT 400 KV HVDC (1 cable)	% IMPACT 525 KV HVDC (1 cable)	# occurences Tropical Cyclone (117 year)
Current Installations	25	46	29	53	1064	9.7%	3.2%	2.4%	0.8%	1.6%	0.5%	0.3%	0.2%	60 to 80
Break-even AC/DC	50	93	57	106	2128	19.3%	6.4%	4.8%	1.6%	3.2%	1.1%	0.5%	0.4%	60 to 80
HVDC significant	75	139	86	160	3191	29.0%	9.7%	7.3%	2.4%	4.8%	1.6%	0.8%	0.6%	60 to 80
Farthest Permit US	100	185	115	213	4255	38.7%	12.9%	9.7%	3.2%	6.4%	2.1%	1.1%	0.8%	40 to 80
Farthest Permit IEA Outlook	200	370	229	426	8510	77.4%	25.8%	19.3%	6.4%	12.8%	4.3%	2.1%	1.6%	20 to 80
Hurricane zone 1	250	463	287	532	10638	96.7%	32.2%	24.2%	8.1%	16.0%	5.3%	2.7%	2.0%	20 to 40
Hurricane zone 2	500	925	574	1064	21275	193.4%	64.5%	48.4%	16.1%	31.9%	10.6%	5.3%	4.1%	5 to 20

40 Volts per kilometer

Landmark Remark	Nautical Mile Mark	Surface Distance (km)	Distance (mi)	Aprx subsea cable L (kM)	Impact (V/cable)	% IMPACT 33KV HVAC (3 cable)	% IMPACT 33 KV HVDC (1 cable)	% IMPACT 132 KV HVAC (3 cable)	% IMPACT 132 KV HVDC (1 cable)	% IMPACT 200 KV HVAC (3 cable)	% IMPACT 200 KV HVDC (1 cable)	% IMPACT 400 KV HVDC (1 cable)	% IMPACT 525 KV HVDC (1 cable)	# occurences Tropical Cyclone (117 year)
Current Installations	25	46	29	53	2128	19.3%	6.4%	4.8%	1.6%	3.2%	1.1%	0.5%	0.4%	60 to 80
Break-even AC/DC	50	93	57	106	4255	38.7%	12.9%	9.7%	3.2%	6.4%	2.1%	1.1%	0.8%	60 to 80
HVDC significant	75	139	86	160	6383	58.0%	19.3%	14.5%	4.8%	9.6%	3.2%	1.6%	1.2%	60 to 80
Farthest Permit US	100	185	115	213	8510	77.4%	25.8%	19.3%	6.4%	12.8%	4.3%	2.1%	1.6%	40 to 80
Farthest Permit IEA Outlook	200	370	229	426	17020	154.7%	51.6%	38.7%	12.9%	25.5%	8.5%	4.3%	3.2%	20 to 80
Hurricane zone 1	250	463	287	532	21275	193.4%	64.5%	48.4%	16.1%	31.9%	10.6%	5.3%	4.1%	20 to 40
Hurricane zone 2	500	925	574	1064	42550	386.8%	128.9%	96.7%	32.2%	63.8%	21.3%	10.6%	8.1%	5 to 20

Assessment

In assessment of this data, findings suggest that the closest offshore wind farms will have low risks associated with GMD, unless HVAC cables are utilized beyond 50 nautical miles. Although use of the HVAC cables for the longer runs is extremely unlikely due to loss and break-even analysis point, doing so would pose significant risk to the transmission cables in all scenarios. This reflects a potential result in costs associated with replacement and may require back up transformers to comply with policies discussed previously.

The 8 volts per kilometer as found to be relative in the TPS-007-1 standard results reflect very low risk, represented by inconsequential, "green" zones almost exclusively where cable size and types would be used. Where not inconsequential, GMD would easily be managed by functionality of the wind turbine and smart controls. This reflects that the standard provides a perception that the threat is non-existent to offshore wind energy, and probably remains to be the case for most frequent solar weather events and an EMP attack.

In these green areas, HVDC and HVAC cable types could feasibly add multiple cables for redundancy and remain within tolerances to easily manage GMD or simply engineer for it within design safety factors.

The severe impact of a major solar weather event could feasibly reach the 20 Volt per kilometer threshold, which reflects potential outage and trip risks in certain configurations to be worried of. HVAC cables, especially in higher voltages, and should probably be avoided for use in cable lengths longer than 400 kilometers. Beyond 200 kilometers, adding the cable redundancy likely necessary could yield potential issues.

The extreme scenario, of 40 volts per kilometer, no longer has inconsequential scenarios while utilizing HVAC cables. While utilizing shorter runs using 33 kV systems, the HVAC impact is rather high, signaling that if to be used, mitigation measures for GMD will be necessary. The length and configuration of these runs could also apply to subsea cables between the wind turbine and the substations out at sea.

The results of this study suggest that using 132 kV lines regardless of the MW capacity and sizing could resolve the GMD risk for smaller offshore wind farms close to the coast, within 25 NM. This solution might be more cost effective than having to provide upfront costs for a redundant transformer. When utilizing HVDC, 200kV and larger cables avoid the risks associated with GMD up to 100 NM, which covers the farthest permitted US project to date.

Furthermore, to reach beyond 50 occurrences in the 117-year period, for tropical storm events, signaling safer zones, the cable lengths would likely need to be more than 200 kilometers. That would consider cable lengths of the 100 NM mark and longer.

The 132 kV and 200 kV size cables could feasibly handle the shorter distances to reach to the lower probability hurricane zones. However, to reach the farthest reaches with redundancy, at 500-kilometer lengths and longer, GMD mitigation will not be avoided. The newest capacity lines, at 525 kV, have the capability to provide resiliency with minor concern of GMD beyond 1000 kilometers, which has the potential to reach the mid-west regions, beyond hurricane risks.

Conclusion.

The findings in this study reflect several potential “partnerships” for future offshore wind farm developments, where there are clear mutual benefits in the construction of extended length HVDC systems. When utilizing larger transmission capability, HVDC cable systems can mitigate the risks of geomagnetic storms and climate related risks at the same time. This reflects potential areas for investment, as the benefit can reach vastly across the United States as a solution to other costly issues.

The study also points out a few vulnerabilities that will exist without future planning outlook. As lengths get longer, transmission capacity for future offshore wind farms can reflect on “lessons learned” from the development history of the HVAC transmission network in the US. Early Offshore Wind farms might not be impacted by geomagnetic disturbances, but with a short distance added either to the East or West, these systems will quickly become susceptible to the risk.

To manage against the risk of geomagnetic storms, utilizing larger transmission cable systems will be an important consideration during the early planning phase. Since these might not be beneficial to smaller or individual projects, a master planning effort would be useful to protect end users from unpredictable outage. This reflects a potential quality management level for early governance.

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